Adaptive Selection of Spreading Code Subsets from Orthogonal Binary Code Sets for Reduced PAPR in MC-CDMA Systems

Sabbir Ahmed† and Makoto Kawai*
Graduate School of Science and Engineering, Ritsumeikan University, Kusatsu City, Japan
Email†: gr045054@ed.ritsumei.ac.jp
Email*: kawai@is.ritsumei.ac.jp

***Abstract*— One of the major concerns with multicarrier CDMA (MC-CDMA) systems is the high peak to average power ratio (PAPR) that can lead to degraded transmission power efficiency. Based on the well known fact that suitable allocation of user spreading codes can be used as a PAPR reduction tool, we in this contribution, investigate the PAPR property of a recently proposed spreading code set called "Orthogonal Binary User (OBU) Codes". Considering different levels of active user densities, we present code allocation table consisting of selected OBU code combinations yielding low PAPR. On the basis of analytical and simulation results, we show that the presented code allocation table is capable of making the system perform better than the well known Walsh-Hadamard codes from both PAPR and BER perspectives.**

***Index Terms*— PAPR, MC-CDMA, Spreading codes, Orthogonal binary user codes, Walsh-Hadamard codes, BER.**

I. INTRODUCTION

Recently, the demand for high-speed wireless multimedia services is growing very rapidly and hence different advanced multiple access technologies are drawing significant attention. Multicarrier code division multiple access or MC-CDMA is one such multiple access method which is an amalgamation of orthogonal frequency division multiplexing (OFDM) and code division multiple access (CDMA) techniques. Considering its capability of offering the combined features of OFDM and CDMA, MC-CDMA appears to be a strong candidate as a multiple access method for future generation wireless communication systems.

But one problem of implementing multicarrier based systems is the large value of peak to average power ratio (PAPR). Since transmitter power amplifiers are often operated near the saturation region, occurrence of high peaks in power envelop of the transmitted signal can lead to severe BER degradation due to non-linear amplification. On the other hand, if amplifiers are operated in the linear region their power efficiency is degraded. Hence, it is desirable that the transmitted signal possesses reduced peaks and in order to achieve this objective, researchers have suggested methods like signal clipping, selected mapping, partial transmit sequences etc. [1-3].

In this context, MC-CDMA systems offer one additional degree of freedom over OFDM systems, i.e., the choice of spreading codes. It has been shown before that the transmitted signal amplitude of MC-CDMA systems is closely related to the collective non-periodic auto-correlation and cross-correlation values of the underlying spreading codes and hence the selection process of spreading codes itself can be used as a tool to characterize the value of PAPR [4, 5].

A survey of related literature reveals that investigations concerning the PAPR issues of MC-CDMA systems, especially with relation to spreading codes, are being carried out mainly from two perspectives. Firstly, studying comparative crest factor (CF) or PAPR of different orthogonal and non-orthogonal spreading code sequences like Walsh-Hadamard (WH), Golay Complementary, Orthogonal Gold and Zadoff-Chu [4-7] and exploring adaptive usage of codes belonging to different code family [7]. And secondly, searching for low PAPR producing codes by investigating different code allocation strategies through the selection of different combinations of codes from a specific code set [5, 8, 9]. All these schemes show peak reduction capability but necessitate some trade off also. For example, applying the concept of adaptive usage of WH and Golay Complementary codes, [7] had proposed a scheme that proved efficient from peak reduction perspective but required transmission of significant amount of side information causing possible negative effect on the system throughput. Again, based on the observation that WH codes show lowest PAPR for systems working at full load capacity, recently [13] proposed a scheme where a system is made to work always at full load by artificially introducing data

Manuscript received December 30, 2009; revised April 7, 2010; accepted May 11, 2010. Part of this paper was presented at the 18th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC '07).

doi:10.4304/jcm.5.7.537-544

symbols from inactive users. This system shows acceptable PAPR reduction, but it is also obvious that it will suffer from high multi-access interference (MAI) and will require high transmission power. Another recent work explores the advantage of different combinations of WH codes through cyclic shift of code sequences for every transmitted symbol [14]. But the introduced mechanism only looks for certain spreading code combinations ignoring a quite large number of other possible combinations. Apart from the computational complexity, it also requires transmission of side information on every occasion a user symbol changes. Thus for higher order modulation the system complexity will be very high. On the other hand, [5, 9] proposed WH sequence based code allocation table for reduced PAPR where creating the code allocation table is a one time activity which is performed before the system goes into operation and thus the requirement of side information is much less compared to [7, 14].

In light of the issues discussed so far, we were motivated to explore the effects of new spreading codes in reducing the PAPR problem of MC-CDMA; a potential future multiple access systems capable of very high data rates. In this endeavour, here in this study our objective is to consider a recently proposed orthogonal set of binary code sequences called orthogonal binary user (OBU) codes [10]. Re-organizing the structure of our previous work [15] based on the OBU code set, here at first we demonstrate the construction of code allocation table as was done in [5, 9]. Then we propose a different variant of code allocation strategy with less computational complexity yet near about same performance. We analyze both single and multiuser scenario, compare the peak property of OBU code with that of WH codes both analytically and with simulation. Finally, we show that codes from our constructed code allocation table perform better compared to corresponding WH codes from both PAPR and BER perspectives.

II. System Description

The transmitter block diagram of a downlink MC-CDMA system is shown in Fig. 1 [7, 9]. Here, $d^{(k)} = \left[d_1^{(k)},\ d_2^{(k)},..,\ d_M^{(k)}\right]$ denotes M modulated data symbols of the kth user, $k = 1,\ 2,....,\ K$. These serial data symbols are at first converted into M parallel symbols. As a result, the symbol rate is reduced by a factor of M. After this serial-to-parallel conversion, each symbol is frequency domain spread by a user spreading code $C^{(k)} = \left[c_1^{(k)},\ c_2^{(k)},..,\ c_L^{(k)}\right]$ where L denotes the length of the spreading code. It means every symbol on each of the M parallel paths is copied L times and then multiplied by each chip of the spreading code simultaneously. In the next stage, frequency domain spread data symbols from all the other users are added on an element-by-element basis. The summed spread symbols from all the users are then fed into a frequency interleaver. The function of the interleaver is to achieve frequency diversity by placing

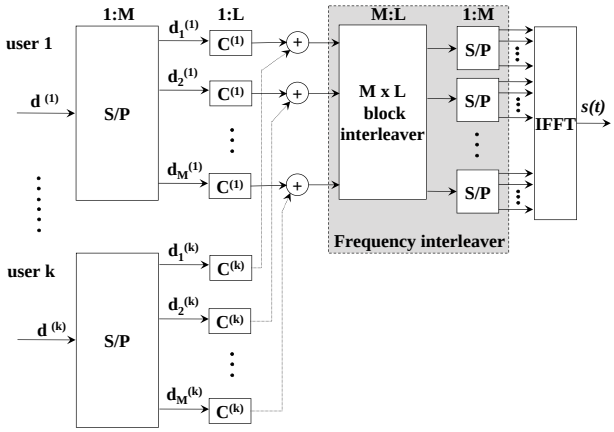

Figure 1. MC-CDMA Transmitter.

chip-symbol elements that correspond to the same symbol on subcarriers that are a distance M apart. After frequency interleaving, the symbol elements are fed into an MxL point IFFT block for OFDM operation. The output samples are then converted back into serial data to generate the complex baseband signal $s(t)$. This signal for an MC-CDMA symbol $0 \le t \le Ts$, can be expressed as,

$$s(t) = \sum_{m=1}^{M} \sum_{l=1}^{L} \sum_{k=1}^{K} d_m^{(k)} c_l^{(k)} e^{j2\pi\{M(l-1)+(m-1)\}t/T_s} \tag{1}$$

The definition of PAPR for an MC-CDMA symbol is given by (2).

$$PAPR = \frac{\max\limits_{0 \le t \le T_s} \left|s(t)\right|^2}{E\left[\left|s(t)\right|^2\right]} \tag{2}$$

In this connection, another parameter of interest is the crest factor (CF) whose relationship with PAPR is expressed by (3).

$$CF = \sqrt{PAPR} \tag{3}$$

This parameter has been used in some of the previous related studies [4-6] and we in this study also consider CF as the measure of variation of the transmission signal's envelop.

III. Spreading Codes

As mentioned before the focus of this study is the OBU code set. For comparison, we chose WH code set since they have been studied extensively in the past. For example references [5-7] showed that Golay complementary codes show better PAPR performance compared to other orthogonal codes at low active user density but WH is a better choice at medium or heavy user densities. Moreover, with respect to employing WH codes in multiuser environment, significant improvement in PAPR has been reported through methodical allocation of user code other than selecting them in a straight forward manner [5, 8, 9, 14].

A. Walsh-Hadamard Codes (WH Codes)

Walsh-Hadamard code is generated from a Hadamard matrix whose rows form an orthogonal set of codes. The codes sequences in this code set are the individual rows of a Hadamard matrix. Hadamard matrices are square matrices whose entries are either +1 or -1 and whose rows and columns are mutually orthogonal. If N is a non-negative power of 2, the NxN Hadamard matrix, is defined recursively as follows.

$$H_{2n} = \begin{bmatrix} H_n & H_n \\ H_n & H_{-n} \end{bmatrix}, \quad H_2 = \begin{bmatrix} +1 & +1 \\ +1 & -1 \end{bmatrix} \quad (4)$$

B. Orthogonal Binary User Codes

Reference [10] proposed these codes and reported that they were constructed through performing search operations in the binary sample space that consisted of zero mean and linear phase codes only. Later they were expanded for non-linear phase code also [11]. In contrast to WH codes, the OBU codes do not necessitate the condition that there can be only one code in the set for a given number of zero crossings. Again, for WH codes, decimal values of all n-bit codes are multiples of either $2^{(n/2)} + 1$ or $2^{(n/2)} - 1$. OBU codes do not impose this restriction. Rather, efforts were made to reduce the number of codes that fulfill this criterion in order to avoid codes that are common to WH codes. Following all these principles, the authors of [10] have shown that for a given code length, more than one OBU code sets can be formulated. In this context, one may remember that for a given code length there exists only one set of WH codes. Since shorter code length implies smaller binary sample space, there exist a considerable number of short OBU codes that are common with same length WH codes. But this number reduces as the code length becomes higher. Table I shows an example of a typical 16 bit OBU code set. For the sake of convenient representation, the codes are shown as decimal numbers. All the occurrences of "-1" bits in a code sequence is at first replaced by "0" bits and then the decimal equivalent of the code sequence is calculated and shown on the table.

TABLE I.
EXAMPLE OF 16 BIT ORTHOGONAL BINARY USER CODE SET

Code index	Decimal notation
1	65535
2	383
3	3727
4	39321
5	12979
6	42405
7	50115
8	15683
9	21717
10	43605
11	52275
12	23333
13	61455
14	26393
15	26857
16	38505

III. ANALYTICAL STUDY

In the context of PAPR, one important property of spreading codes is its aperiodic auto-correlation value. If we consider the L-bit long xth code $C^{(x)} = \left[c_1^{(x)},\ c_2^{(x)},\ldots,\ c_L^{(x)}\right]$ from a code set having P distinct code sequences, the aperiodic auto-correlation $AC_n^{(x)}$ is given by,

$$AC_n^{(x)} = \sum_{i=0}^{L-n-1} c_i^{(x)} [c_{i+n}^{(x)}]^* \quad (5)$$

where [ ]* refers to the conjugate operation.

Figure 2 depicts the comparative collective aperiodic auto-correlation of 16 bit OBU and WH codes. It shows that OBU codes in general exhibits lower values of aperiodic auto-correlation than that of WH codes.

In MC-CDMA system, since the power spectrum of spreading code is related to the transmitted signal amplitudes, PAPR can be estimated by analyzing the correlation properties of those codes. Based on this principle, [9] proposed an algorithm for finding code combinations resulting in least PAPR. Following that algorithm, the comparative minimum normalized peaks of WH and OBU codes are shown in Fig. 3. It is evident that some selected OBU code combinations possess better aperiodic auto-correlation values than corresponding WH codes combinations and hence show lower peak values for all most all the user cases.

However, in multiuser environment, where multiple codes are used simultaneously, apart from aperiodic auto-correlation, a message dependent parameter called the collective aperiodic cross-correlation has significant effect on PAPR [5]. This parameter is defined by,

$$CC_n = \sum_{x=0}^{P-1} \sum_{y=0, y\neq x}^{P-1} b^{(x)} [b^{(y)}]^* CC_n^{(x),(y)} \quad (6)$$

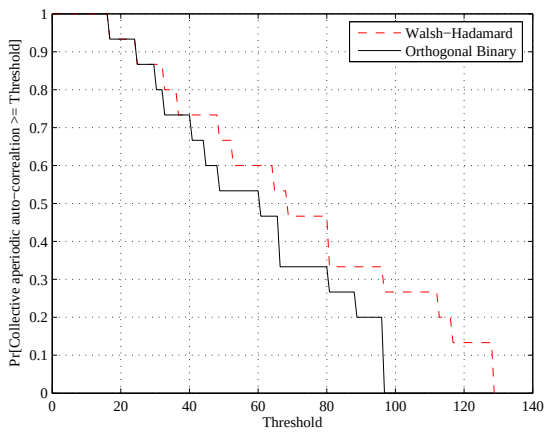

Figure 2: Comparative aperiodic auto-correlation.

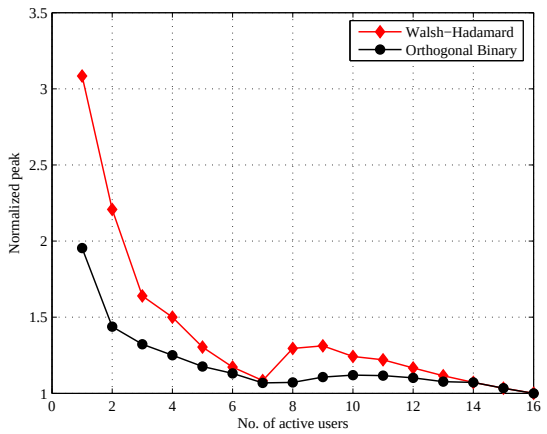

Figure 3: Minimum normalized peak for different active user level.

However, in multiuser environment, where multiple codes are used simultaneously, apart from aperiodic auto-correlation, a message dependent parameter called the collective aperiodic cross-correlation has significant effect on PAPR [5]. This parameter is defined by,

$$CC_n = \sum_{x=0}^{P-1} \sum_{y=0, y\neq x}^{P-1} b^{(x)} [b^{(y)}]^* CC_n^{(x),(y)} \tag{6}$$

where, $b^{(x)}$ and $b^{(y)}$ are message symbols from the xth and the yth user respectively and $CC_n^{(x),(y)}$ is the aperiodic cross-correlation between xth and yth codes given by,

$$CC_n^{(x),(y)} = \sum_{i=0}^{L-n-1} c_i^{(x)} [c_{i+n}^{(y)}]^* \tag{7}$$

In our study, we consider 16QAM as the modulation method where the number of possible distinct message symbols is large compared to BPSK or QPSK. Thus in addition to the just presented analytical result, a comprehensive simulation is performed.

IV. Spreading Code Allocation Methodology

Considering the architecture of Fig. 1 and our previous discussion with respect to spreading codes, the symbols just prior to interleaving can be represented as,

$$\begin{bmatrix} Q_1 \\ Q_2 \\ . \\ Q_M \end{bmatrix} = \begin{bmatrix} d_1^1 & d_1^2 & \dots & d_1^K \\ d_2^1 & d_2^2 & \dots & d_2^K \\ \dots & .. & \dots & .. \\ d_M^1 & d_M^2 & \dots & d_M^K \end{bmatrix} x \begin{bmatrix} c_1^{(1)} & c_2^{(1)} & \dots & c_K^{(1)} \\ c_1^{(2)} & c_2^{(2)} & \dots & c_k^{(2)} \\ \dots & \dots & \dots & \dots \\ c_1^{(K)} & c_2^{(K)} & \dots & c_K^{(K)} \end{bmatrix} \tag{8}$$

where, we have considered the length of spreading codes equal to that of total number of maximum possible users. Here, the spreading codes have been allocated on a plain sequential manner, i.e., user index and code index is same. But it is possible to check other combinations of code allocation as discussed below resulting in different values of PAPR.

If we consider a code set consisting of 16 unique orthogonal code sequences and 8 active users in the system, we find that there can be as many as $C_8^{16} = 12870$ unique different possible ways of allocating codes to the users. And since the collective aperiodic auto and cross correlation values of these combinations may vary, so may the CF produced by them. As a result, finding the best code combinations, i.e., the combinations that produce lowest CF, is of interest. But, recalling the fact that the collective aperiodic cross correlation is dependent on message symbols [5], a perfect estimation of lowest CF producing code combination requires consideration of all possible message combinations along with all possible code combinations. For example with 16QAM modulation, if n number of users each send 1 symbol, 16^n no. of different symbol combinations is possible. So, the number of possible code sequence-symbol combination comes to C_n^{16} x 16^n. The second term increases exponentially with increasing n. But, since higher user density results in less PAPR [5-7], relatively low values of n is of prime concern.

We define two alternative methods of the spreading code allocation strategies. We name the first method as best code allocation and the second one as the optimum code allocation method.

A The Best Code Allocation Approach

In the first method, users are assigned specific spreading codes from all the available spreading codes in such a manner so that the resultant crest factor (CF) becomes minimum. This approach considers each user case discretely and formulates code combinations yielding least CF for those cases. For example, if the number of active users is k and the total number available spreading codes is N, $[C^{(1)}, C^{(2)}, \dots, C^{(k)}]$ is chosen from $[C^{(1)}, C^{(2)}, \dots, C^{(N)}]$ so that the CF of the transmit signal is minimum. When choosing the best spreading combination, the effect of user data is also taken into account by considering random combinations of input symbols from all users.

The method is illustrated in Fig. 4. Here, as soon as the state of the user case changes, the entire code set is searched to find the new code combination producing lowest CF. For example, if the number of users change

1. Start with user case n = 1.

2. Select a code combination having n number of code sequences from total available N codes. within the N length code set .

3. Generate random 16 QAM data frames for all n users

4. Apply those code sequences to perform MC-CDMA operations.

5. Calculate CF from the time domain signal.

6. Repeat steps 3 to 5 for a predefined number of times and calculate average CF.

7. Repeat steps 2 to 6 for $C_n^N - 1$ times for all other combinations.

8. Record the lowest CF and corresponding code combination.

9. Increment n by 1 and repeat steps 2 to 8 for all other possible values of n.

Figure 4. Principle of the best code allocation approach.

1. Start with user case n = 1.

2. Select a single code from total available N-(n-1) codes within the N length code set

3. Generate random 16 QAM data frames for all n users

4. Apply those code sequences to perform MC-CDMA operations.

5. Calculate CF from the time domain signal.

6. Repeat steps 3 to 5 a predefined number of times and calculate average CF.

7. Repeat steps 2 to 6 for $C_n^{N-(n-1)} - 1$ *times for all other combinations.*

8. Record the lowest CF and corresponding code combination.

9. Increment n by 1 and repeat steps 2 to 8 for all other possible values of n.

Figure 5. Principle of the optimum code allocation approach.

from 4 to 5, $C_5^{16} = 4368$ possible code combinations are searched to find the best one.

A drawback of this method is that on the arrival of a new user, besides allocating code to this user, it necessitates that all users who were in the system before the change of user case occurred also get their spreading codes reassigned since the new code combination may not preserve the previously allocated codes. This may result in an additional overhead from switching and resource allocation perspective and thus may increase the system complexity to a higher extent.

B The Optimum Code Allocation Approach

In contrast to the first approach, this approach, considers change of user cases as a continuous process. Here, codes allocated to users on a particular user case are marked as used and new users are assigned codes only from those codes that have not been allocated yet. Returning to the previous example, when the number of users changes from 4 to 5, already allocated user codes are not included in the search space for finding the code to be allocated to user number 5. As a result, only $C_1^{12} = 12$ code combinations are now searched to find the best combination. This approach has the drawback of showing possible inferior CF performance compared to the previous approach as the search space is limited. But computational complexity for building the code allocation table is reduced and also no additional overhead related to dynamically changing already allocated user codes is present as was the case with the other approach. The scenario is depicted in Fig. 5. We call it optimum code allocation approach since it optimizes system complexity at the cost of possible higher crest factor.

In general for both the approaches, the base station transmits the code allocation table to a new user along with the user index. Then, for the best allocation approach, a notification is sent to all existing users whenever a new user arrives. But in the second approach, the existing users do not need any notification in case of new arrivals.

V. SIMULATION MODEL AND PERFORMANCE EVALUATION

TABLE II.
SIMULATION PARAMETERS

Modulation scheme	16 QAM
Spreading code length	16
No. of symbols per frame	4
No. of subcarriers	64
Non-linear amplifier model	SSPA
Level of non-linearity, r	3

Our simulation was based on the transmitter model shown in Fig. 1 In addition, for analyzing bit error rate, we considered a solid state power amplifier (SSPA) model [12], an AWGN channel and a simple correlator based receiver architecture. The salient simulation parameters are listed in Table II. And the non-linear characteristic of the amplifier is given by (9).

$$F[x] = \frac{x}{\left[1 + \left(x/A\right)^{2r}\right]^{1/2r}} \tag{9}$$

where, x is the amplitude of the input signal, A is the saturated output level and r is the parameter that decides the level of non-linearity. For fixing amplifier operating point we considered the parameter output back-off (OBO) which is given by.

$$OBO = 10\log_{10}\left(\frac{P_{sat\ out}}{P_{out}}\right) \tag{10}$$

where, $Psat_{out}$ is the saturation power referred to the output and $Pout$ is the output power.

A. Single User Scenario

In the context of uplink communication, since the signals from individual users are amplified by different amplifiers, every spreading code sequence of a particular code set is examined individually. Our simulation result shown in Fig. 6 illustrates the comparative CF values of WH and OBU codes. Here, CF values for all the 16 distinct sequences available from 16 bit long WH and OB code set are plotted and compared on an individual basis. The results show that 50% of OBU codes generate a lower CF than corresponding WH codes and 93.75% of OBU codes produce a lower or equal CF than corresponding WH codes. Comparison was also done with the help of complementary cumulative distribution function (CDF) of CF considering all the code sequences. This is depicted in Fig. 7 and it clearly shows the superior CF properties of OBU codes over WH codes.

B. Multiuser Scenario

In a synchronized downlink communication environment, the base station transmits a signal that constitutes of summed signals of multiple users spread by different spreading codes. Hence the CF property of the transmitted signal, as mentioned before, is determined by the collective properties of individual spreading codes.

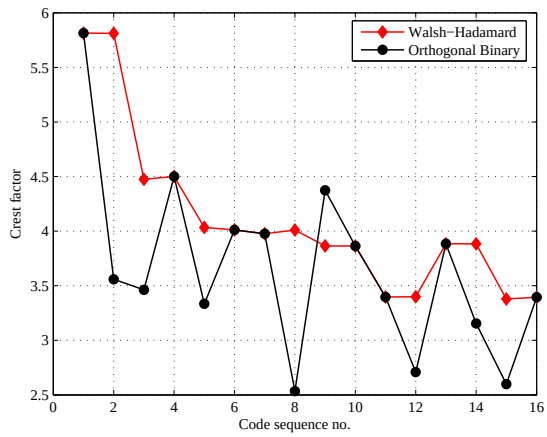

Figure 6. Crest factor of 16 bit long codes.

TABLE III.
THE CODE ALLOCATION TABLE

No. of active users	Best combinations	Optimum combinations
1	0x0100	0x0100
2	0x0102	0x0102
3	0x0112	0x0112
4	0x4806	0x0912
5	0x6901	0x4912
6	0x6816	0x6912
7	0x6916	0x6916
8	0x16E9	0xE916
9	0x16EB	0xE917
10	0x96EB	0xE997
11	0xD7E3	0xE99F
12	0xBFE9	0xE9DF
13	0xF7F9	0xEBDF
14	0xDFDF	0xFBDF
15	0xFFFD	0xFFDF
16	0xFFFF	0xFFFF

We constructed the code allocation table for OBU codes considering a multiuser system that can support a maximum of 16 simultaneous users. For each possible user cases, i.e., 1 to 16, we simulated the system considering 4 random 16QAM symbols per frame. Thus one MC-CDMA symbol consisted of a minimum of 4 to a maximum of 16x4=64 QAM user symbols spread by 16 bit long spreading codes. We put more emphasis on the spreading codes by examining their all possible combinations and for each of this combination the user symbol effect is included by considering 100 frames random data.

Table III shows the code combination values resulting from the two allocation approaches. Here, the combination values are represented in hexadecimal format [5] which is explained using an example. Let us take the particular user case of a total of 5 active users in the system. The best code combination value for this case reads $(6901)_{16}$. When this hexadecimal number is converted into its binary equivalent, it becomes $(0110\ 1001\ 0000\ 0001)_2$. This binary string has the bit value of "1" in its 2nd, 3rd, 5th, 8th and 16th position from the MSB and it implies that the combination of codes having the indices of 2, 3, 5, 8 and 16 (refer to Table I) produces the lowest CF for all possible combinations.

For the same user case, the optimum combination displays the values of $(4912)_{16}$, i.e., $(0100\ 1001\ 0001\ 0010)_2$ which means codes having the indices of 2, 5, 8, 12 and 15 represent the code combination with the lowest CF value resulting from the optimum allocation approach. Again, if we move to the next user case and check the optimum combination value, we find that it shows $(6912)_{16}$, which when converted to binary is $(0110\ 1001\ 0001\ 0010)_2$. By comparing this value with that of the previous user case we find that only the code with an index of 3 has been added without any change to the already allocated code indices. But for the best allocation approach, comparing the same two user cases it is found that there are changes associated with more than one bit positions in the binary strings representing the code combinations. These two observations confirm the difference between the two code allocation approaches that was mentioned earlier.

Figure 8 illustrates the comparative results of different code allocation approach for OBU codes. As is evident from this figure, sequential allocation shows very poor CF values at low user densities but its performance gradually improves elsewhere. By sequential allocation we refer to allocation of codes in the same order as found on the code set table.

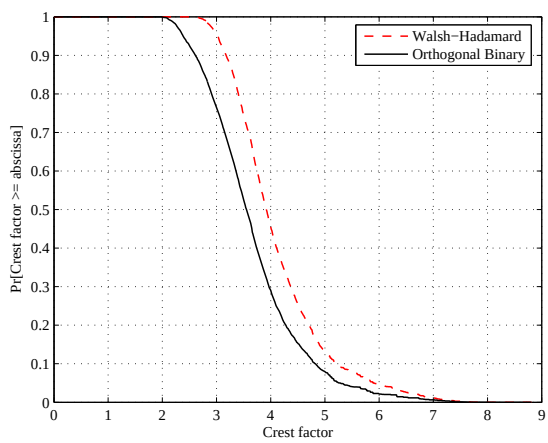

Figure 7. Comparative CDF of crest factors.

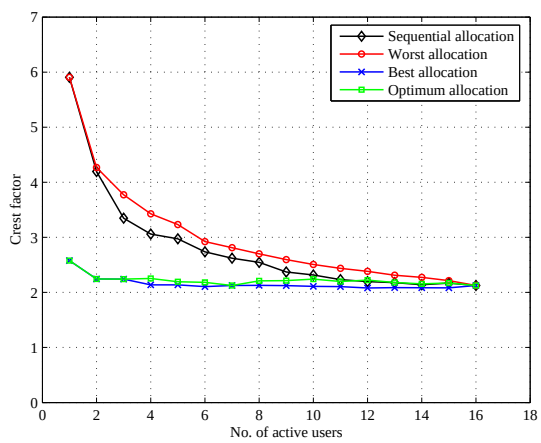

Figure 8. Crest factor of OBU codes for different allocation method.

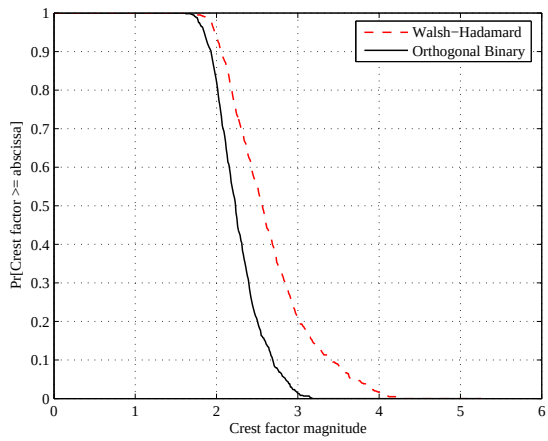

Figure 9. Comparative crest factor at low user density.

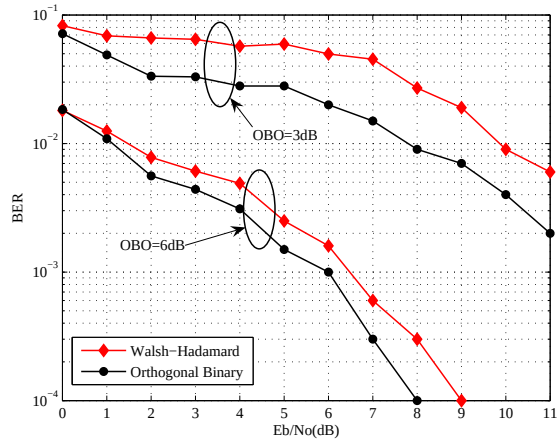

Figure 10. Comparative bit error rate

That means user k is assigned the code sequence having the index k and so on. CF plots for the other three cases found in this illustration are not sequential, i.e., user index and code index are necessarily not the same. In this respect, the worst allocation corresponds to those code combinations which yield maximum CF. This finding came up when different combinations were being tested for CF comparison. It is understandable that these are the least desired combinations. The unintended presence of these code combinations can be eliminated by avoiding random code allocation.

Now, the last two graphs of Fig. 8 are of special interest as they correspond to best and optimum code allocation approaches. Compared to sequential allocation approach, both of them show an improvement in performance. Specifically in the region of low user density their superiority over sequential approach is noticeable. It is interesting to notice that optimum combination approach demands less computational and implementational overhead compared to best allocation approach and yet demonstrates almost the same performance.

Best code combinations formulated from WH codes have been reported before [5, 9]. Since the problem of WH codes is to generate higher peaks at low user density, we decided to perform a relative CF comparison of best code combinations of OBU and WH codes focusing on relatively lower number of total active users. For this simulation, we chose a user density of <=37.5% and compared the complementary CDF of CF of those two best code combinations as shown in Fig. 9. From this figure, we find that best combinations of OBU codes perform better than the corresponding WH best code combinations.

Finally, Fig. 10 shows the comparative BER depicting the effect of power amplifier non-linearity on the peak produced by the two best combination spreading codes. The BER simulation was carried out by concentrating on the region of low user density by selecting the case of 4 active users. Two different level of amplifier OBO, i.e., 3dB and 6dB were investigated, and for both the cases the results show that the best combinations of OBU codes are less affected by amplifier non-linearity than the corresponding WH best code combinations. From these results, it is obvious that selected code subsets from the OBU code set exhibit better performance than WH code subset.

VI. Conclusions

Multicarrier systems often possess high peaks in their time domain signal that may lead to non-linear amplification and there by cause severe BER degradation. CF is a parameter that quantifies the peaks in a signal and with the help of this parameter, we analyzed the comparative performances of WH codes and OBU codes in the context of an MC-CDMA system that uses a non-linear amplifier and works under the influence of an AWGN channel. We found that in a single user scenario the OBU codes produce lower CF values than WH codes.

And for a multiuser environment, when spreading codes are applied in a sequential manner, the OBU codes show decreasing CF with increasing user density. Being, motivated by the approaches of [5, 9], we constructed code allocation tables by selecting low CF producing code subsets. In this context, we also introduced the optimum allocation approach that minimizes system complexity yet achieves good performance. Our analytical and simulation results showed that selected code combinations from the OBU code set exhibit better performance than corresponding WH codes. On the basis of our study results and the fact that OBU code and non-linear phase Walsh like orthogonal codes give better performance than WH codes in conventional single carrier CDMA systems [10, 11], we affirm that for multiuser MC-CDMA systems, use of specific OBU code combinations as spreading codes can lead to considerable reduction in CF and thus result in improved system performance.

The code allocation table only considers increase in user cases. In case of decrease in the number of users some codes will be released. It is important to consider this scenario also in order to have a more efficient and practical code allocation procedure. We consider it as a scope of future work.

REFERENCES

[1] X. Li and L. J. Cimini, "Effects of clipping and filtering on the performance of OFDM", *IEEE Communications Letters*, vol. 2, no. 5, pp. 131-133, May 1998.

[2] R. W. Bauml, R. F. H. Fischer and J. B. Huber, "Reducing the peak-to-average power ratio of multicarrier modulation by selected mapping", *IEE Electronics Letters*, vol. 32, no. 22, pp. 2056-2057, October 1996.

[3] L. J. Cimini and N. R. Sollenberger, "Peak-to-average power ratio reduction of an OFDM signal using partial transmit sequences", *IEEE Communications Letters*, vol. 4, no. 3, pp. 86-88, March 2000.

[4] B. J. Choi, E. L. Kuan and L. Hanzo, "Crest factor study of MC-CDMA and OFDM", *Proc. IEEE VTC 1999-Fall*, vol. 1, pp. 233-237, 1999.

[5] L. Hanzo, M. Munster, B. J. Choi and T. Keller, "Advanced peak factor reduction techniques, in OFDM and MC-CDMA for broadband Multi-user Communications, WLANs and broadcasting", *WILEY-IEEE press*, pp. 288-306, 2003.

[6] S. Nobilet, J-F. Helard and D. Mottier, "Spreading sequences for uplink and downlink MC-CDMA systems: PAPR and MAI minimization", *ETT*, vol. 13, no. 5, pp. 465-474, 2002.

[7] H. Ochiai and H. Imai, "OFDM-CDMA with peak power reduction based on the spreading sequences", *Proc. IEEE ICC '98*, pp. 1299-1303, June 1998.

[8] N. Hathi, I. Darwazeh and J. O'Reilly, "Peak-to-average power ratio performance comparison of different spreading code allocation strategies for MC-CDMA and MC-DS-CDMA", *Electronics Letters*, vol. 32, no. 20, pp. 1219-1220, September 2002.

[9] K. Kang, K. Choi and S. K. Shin, "Reduced search for optimum code sets to reduce PAPR in MC-CDMA System", *5th International Symposium on Wireless Personal Multimedia Communications*, vol. 1, pp. 135-139, October 2002.

[10] R. Poluri and A. N. Akansu, "New orthogonal binary user codes for multiuser spread spectrum communications", *13th European Signal Processing Conference, Antalya, Turkey*, September 4-8 2005.

[11] A. N. Akansu and R. Poluri, "Walsh-Like Nonlinear Phase Orthogonal Codes for Direct Sequence CDMA Communications", *IEEE Transactions On Signal Processing,* Vol. 55, No. 7,pp. 3800-3806, July 2007.

[12] C. Rapp, "Effects of HPA-nonlinearity on a 4-DPSK/OFDM signal for a digital sound broadcasting system," *Proc. Second European Conference on Satellite Communications*, Liege, Belgium, pp. 179-184, October 1991.

[13] L. A. P. Hernández and M. G. Otero, "User Reservation Approach for Peak-to-Average Power Ratio Reduction in MC-CDMA Systems", *IEEE 69th Vehicular Technology. Conferenc*e, Barcelona, Spain, April 26-29, 2009.

[14] L. Yang and E. Alsusa, "Dynamic Code-allocation based PAPR Reduction Techniques fro MC-CDMA Systems", *2007 IEEE Wireless Communications and Networking Conference*, Hongkong, March 11-15, 2007.

[15] S. Ahmed, T. Noguchi and M. Kawai, "Selection of Spreading Codes for Reduced PAPR in MC-CDMA Systems," *18th IEEE Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'07)*, Athens, Greece, September 2007.

Sabbir Ahmed received his B.E. degree in Electrical and Electronics from Bangladesh University of Engineering and Technology (BUET), Bangladesh and M.E. degree in Information Science and System Engineering from Ritsumeikan University, Japan in 1999 and 2007 respectively. He is currently enrolled as a PhD student in the same school from where he did his M.E. His research interests include mobile and wireless communication, multicarrier systems, multiple access methods and non-linear effects. He received the Best Student Paper Award at the 25th AIAA International Communication Satellite System Conference (ICSSC '07) held in Seoul, South Korea, 2007.

Makoto Kawai was born in 1949. He received B.S., M.S. and Dr. Eng. Degrees in electrical engineering from Kyoto University, Kyoto, Japan, in 1972, 1974 and 1987, respectively. During 1974 and 1999 he worked mainly for research and development of wireless communication systems at Nippon Telegraph and Telephone Corporation (NTT) and also worked at Advanced Telecommunications Research Institute International (ATR) from 1996 to 1999. He was an associate professor at Graduate School of Informatics, Kyoto University from 1999 to 2003. He is now a professor of Graduate School of Science and Engineering and College of Information Science and Engineering, Ritsumeikan University, Shiga, Japan. He is a member of IEEE, AIAA, IEICE, IPSJ and IEEJ.